EDGEWOOD
CHEMICAL BIOLOGICAL CENTER

U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND

ECBC-TR-713

TACTICAL GARBAGE TO ENERGY REFINERY

James J. Valdes

RESEARCH AND TECHNOLOGY DIRECTORATE

Jerry Warner

DEFENSE LIFE SCIENCES

DEFENSE LIFE SCIENCES
McLean, VA 22101

October 2009

Approved for public release;
distribution is unlimited.

20091223223

ABERDEEN PROVING GROUND, MD 21010-5424

Disclaimer

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* XX-10-2009	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* Jul 2007 - Oct 2008

4. TITLE AND SUBTITLE
Tactical Garbage to Energy Refinery

5a. CONTRACT NUMBER
W911SR-07-C-0052

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Valdes, James J. (ECBC); and Warner, Jerry (Defense Life Sciences)

5d. PROJECT NUMBER
STTR A04-T019

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DIR, ECBC, ATTN: RDCB-DR, APG, MD 21010-5424
Defense Life Sciences, LLC., 6832 Old Dominion Drive, Suite 206, McLean, VA 22101

8. PERFORMING ORGANIZATION REPORT NUMBER
ECBC-TR-713

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT-LIMIT 200 WORDS
An emerging concept is the convergence of "green practices" such as systemic sustainability and renewable resources with military operational needs. Tactical biorefineries leverage biotechnology and thermochemical processes for energy production and are designed to address two significant problems in an overseas crisis deployment. The first problem is access to dependable energy. Operations in Southwest Asia have shown that, despite advanced logistics and host nation resources, access to fuel, particularly during the early months of a crisis, can be difficult. The second is the cost and operational difficulties for waste disposal. Delivery of materiel to forward positions creates huge volumes of waste, and its removal inflicts a costly and complex logistics and security overhead on U.S. Forces. Deployable tactical biorefineries are being designed to convert military field waste into immediately usable energy at forward operating bases, on the battlefield or in a crisis area. In addition to providing operational benefits to U.S. Forces, these systems will provide significant cost savings by reducing the need for acquisition and distribution of fuel via convoys that are vulnerable to attack. Tactical biorefineries would also serve a useful role in other military programs that support disaster relief or post-combat stabilization.

15. SUBJECT TERMS
Biofuel Tactical energy Synthetic gas Fermentation Downdraft gasifier

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Sandra J. Johnson
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U	UL	31	(410) 436-2914

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Blank

PREFACE

The work described in this report was authorized under Contract No. STTR A04-T019, Phase III, Project No. W911SR-07-C-0052. This work was started in July 2007 and completed in October 2008.

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

This report has been approved for public release. Registered users should request additional copies from the Defense Technical Information Center; unregistered users should direct such requests to the National Technical Information Service.

Acknowledgments

The authors gratefully acknowledge the funding support of the U.S. Army's Rapid Equipping Force, the Small Business Technology Transfer Research program, and the U.S. Army Research, Development and Engineering Command. We also thank the many forward deployed personnel at Victory Base Camp, Iraq, for their support on the ground. Special thanks to Donna Hoffman for pre-deployment and deployment support and for extensive editing and preparation of the manuscript.

Blank

CONTENTS

FIGURES

TABLES

Blank

TACTICAL GARBAGE TO ENERGY REFINERY

1. INTRODUCTION

The initial challenge was to mate the waste streams produced by small tactical units with technologies that were net energy positive at that scale. The Tactical Garage to Energy Refinery (TGER) system was the result of a high level of optimization "from the trash up" and required a through scientific analysis and technology selection process with full consideration of the context within which it would be operating.

The TGER is a trailer mounted system capable of converting waste product (paper, plastic, packaging, and food waste) into electricity via a standard 60kW diesel generator. Additionally, if available, the system can use local biomass. Waste materials are converted into bio-energetics that displaces the diesel fuel used to power the generator set. The system also co-produces excess thermal energy that can be used via a "plug and play" heat exchanger to drive field sanitation, shower, laundry, or cooling devices. With additional engineering, the TGER could include a small subsystem to recover water introduced with the wet waste and produce potable water to further reduce any logistics overhead. The systems would require a small "laundry packet" of enzymes, yeasts, and industrial antibiotics to support the biocatalytic subsystem. The residuals from this conversion are environmentally benign including simple ash (which can be added to improve soil for agriculture) and carbon dioxide.

There are numerous wastes to energy technologies, each with varying efficiencies and capabilities to digest complex waste streams.[1] Figure 1 breaks the problem set down to net power output (x axis) verses the type of waste (y axis) and shows the range of applications from landfill to onsite or tactical utilities. Incineration, for example, will handle all waste types including hazardous materials and metals but has only 10% net power output at best and is most suited to large static operations such as landfills. By contrast, biocatalytic (i.e., enzymatic) approaches have much more limited ability to handle waste but are relatively efficient (~75%) in terms of net power output.[2] Biocatalytic approaches are therefore more suited to operations in which the waste stream is predominantly food waste and biomass. These two technologies occupy the extremes of this energy return spectrum.

The TGER design is a "hybrid" that uses biocatalytic (fermentation) and thermochemical (gasification) subsystems in a complementary manner to optimize overall system performance and to address the broadest possible military waste stream. The hybrid design is based on detailed analysis of the waste stream combined with a modeling and simulation program unique to the TGER. The objective waste stream includes food and dry material. A system, which included a biocatalytic format for organic such as food and juice materials, and a thermochemical format for solid wastes such as paper, plastic and Styrofoam, would have significant advantages over unitary approaches.

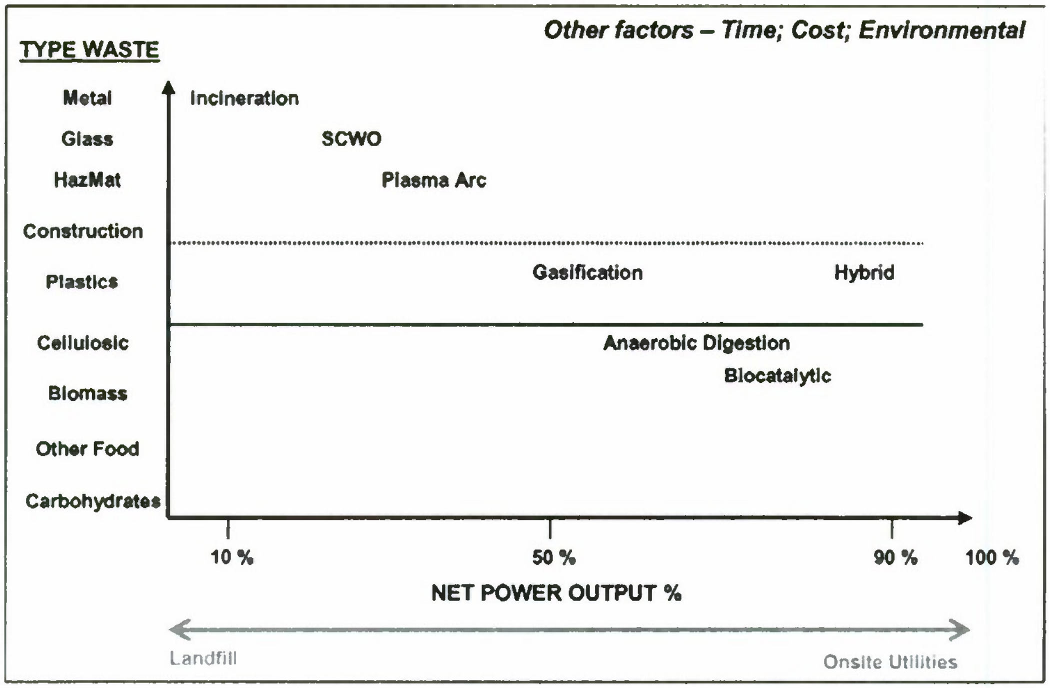

Figure 1. Waste to Energy Technologies

The Energy and Material Balance mathematical model showed that conversion of materials and kitchen wastes to syngas and ethanol would provide sufficient energy to drive a diesel engine and generate electricity. A downdraft gasifier was selected to produce syngas via thermal decomposition of solid wastes. A bioreactor consisting of advanced fermentation and distillation was used to produce ethanol from liquid waste and the carbohydrates and starches found in food waste.

Dry and wet field wastes (with the exception of metal and glass) are introduced into a single material reduction device that reduces the wet and dry waste into a slurry. This slurry is then subjected to a "rapid pass" fermentation run, which converts approximately 25% of the carbohydrates, sugars, starches, and some cellulosic material into 85% hydrous ethanol. The remaining bioreactor mass is then processed into gasifier pellets, which are then converted into producer gas also known as "syngas". The hydrous ethanol and syngas are then blended and fumigated into the diesel engine, gradually displacing the diesel fuel to an estimated 2% pilot drip. The design process model is shown in Figure 2.

Adding the advanced fermentation process to the design of the TGER added no significant energy costs, as heat generated by the engine's exhaust drives the distillation, which is carried out in an 8 ft high column packed with material over which fractionation of ethanol and water occurs. The additions of a few small pumps used to transport the ethanol solution from the fermentation tank to the distillation column and finally to the ethanol storage tank, were the only additional power requirements. The combination of the two waste-to-energy technologies allowed for the remediation of a broader spectrum waste stream (solid and liquid), the ability to extract much more energy from the waste, and operation of the generator at full power due to the anti-knock properties of the hydrous ethanol.

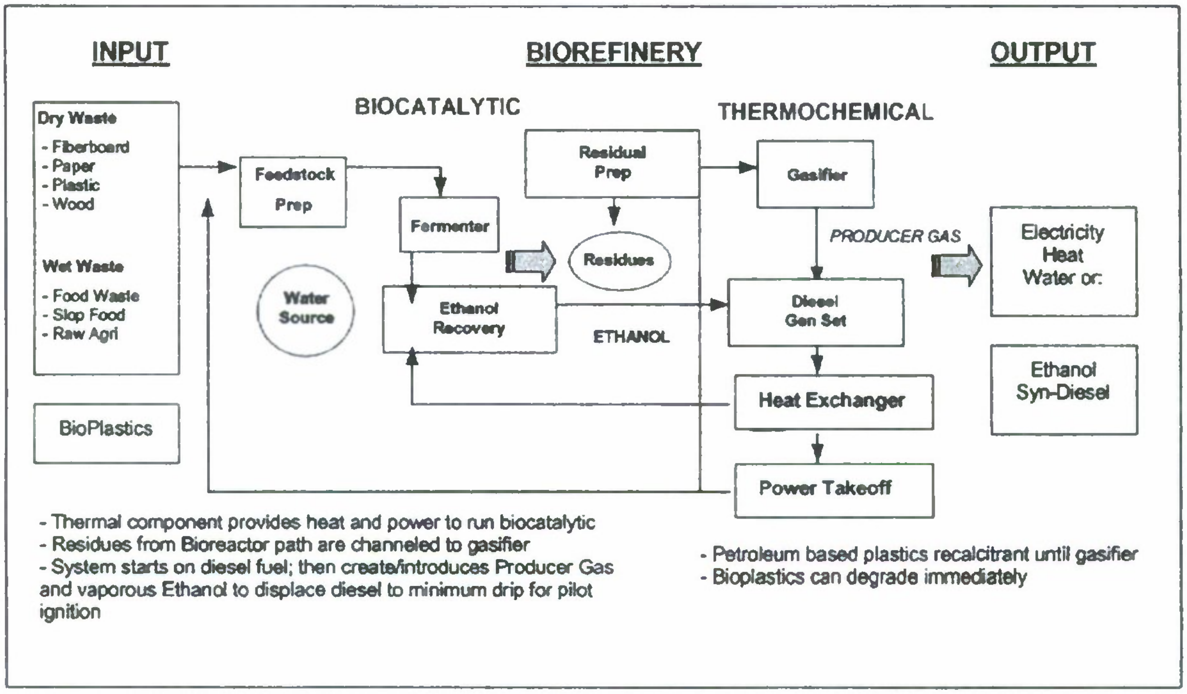

Figure 2. In-line Biorefinery Design Process Model

2. BACKGROUND RESEARCH

There were two key bodies of knowledge that defined our rcsearch and technology transition plan. First, was the development of an understanding of the military context in which the tactical biorefinery was to serve and, second, was to search the available "solution space" of current and future technologies and requirements of relevance.

Within the military context, there were a number of science and technology variables that were considered. These included the type of input biomass, the type or types of biomass processing to be used, the output stream that results, and the kinds of military applications that would be served. A graphic depicting our "solution space" is shown in Table 1.

Table 2 illustrates the relative energy content of differcnt fuels relativc to diesel fuel.[3,4,5] The value of converting organic waste into ethanol is clearly shown. Ethanol has 69% of the energy content that the same volume of diesel fuel has, whereas synthetic gas has only 20% of the energy content of diesel fuel.[6,7] Ignoring the potential energy contained within organic food and liquid wastes would rcsult in a significant loss of energy and reduced dicsel fuel savings.

Table 1. Solution Space for Waste to Energy

Waste	***Technology***	***Energy Product*****	***Military Application Served***
Food Waste (Starch)	Bioprocessing	Ethanol (fluid .69)	Liquid fuel for burners/generators
Food Waste (oil, grease)	*Starch	Methanol (fluid .51)	(primary or fuel additive)
Plastics	*Cellulosic	Bio-oil (fluid)	Gaseous fuel for modified generators
*Petroleum based	Pyrolysis to bio-oil	Biodiesel (fluid .6)	Fuel cells, PEMs generators
*Bio-based	Gasification to energy	Methane (gas .97)	Liquid fuel for advanced batteries
Paper (cellulosic)	Hybrid	Hydrogen (gas .2)	Direct electricity to power grid
Fiber Board (cellulosic)	*Thermal		Hot water for troop use
Locally Agriculture	*Bioprocess	**(form and Energy per unit Volume, Gasoline = 1.0)	

Table 2. Relative Energy Content

Energy Product	Energy Index	Energy per Unit Volume*	
Diesel	1.0	138,000 BTU	48 MJ/kg
Gasoline	.98	125,000 BTU	
Ethanol	.69	84,600 BTU	
Producer Gas	.2		10 MJ/kg
	(*Diesel = 1.0)		

3. MATERIALS AND METHODS

The TGER prototypes were fabricated and commissioned at Purdue University (West Lafayette, IN) and conformed to the following selection criterion:

a. Approach the problem as a "dual optimization" to develop a system that will simultaneously eliminate as much waste as possible while producing as much useful energy as possible.

b. Design of the TGER must be "tuned" to the operational context to ensure an easily available and reliable volume of military waste.

c. The TGER should be designed to be contiguous with the input source of wastes and end user for the output energy product, avoiding any reprocessing or transport costs.

d. The TGER must be operationally and tactically deployable via military airframe and able to be transported on the ground via standard military trailer.

e. The TGER should not need additional manpower or machinery costs for waste separation.

f. The process must minimize parasitic costs such as manpower, water, external energy, etc.

g. The refining process should have minimal residual waste.

h. Additional concerns of hazardous waste, safety, and troop use must be considered, and operation should be amenable to unskilled labor.

The selection of gasification and biocatalytic fermentation has strategic value in that both methods are well demonstrated technologies supported by high levels of research by the Department of Energy and, in the long course, are very likely to improve as new advances are achieved.

Significant new advances in gasification include the introduction of integrated sensors and automated computerized control systems for the process. These recent advances have resulted in gasification technologies with reliable and efficient conversion of waste to energy. Significant recent advances in biocatalytic fermentation include advances in genetically modified or modified via directed evolution enzymes and micro-organisms. Using methods developed at the Laboratory of Renewable Resources Energy at Purdue University, several commercial entities have broken new thresholds in domestic ethanol production techniques by applying new biocatalysts and processes, the result being the economically viable production of ethanol for fuel.[8] Current advances in enzymatic design and development bode well for further methods to reduce what would normally be considered unusable biomass waste (e.g., paper fines from shredded cardboard and other cellulosic wastes) into usable energy, allowing more energy to be harnessed from the same waste stream.

During the commissioning phase of the TGER, the system was able to deliver reliable power with very low parasitic costs required to operate the system internally. The core processes, gasification and fermentation for conversion of waste to energy, worked very well and the unique hybrid combination of thermochemical and biocatalytic technologies proved itself to be of considerable merit. These technologies could easily scale up to support military installations such as hospitals and major troop areas by converting waste into power, hot water, and usable fuel, while eliminating costly waste removal expenses. Installation biorefineries could provide cost savings for U.S. and overseas bases; reduce dependence on petroleum-based energy and support environmentally responsible initiatives, highlighting Department of Defense's support of renewable energy resource technologies.

3.1 Retrofits.

The first TGER prototype (Figure 3) was built as a part of a Phase II Small business Technology Transfer Research (STTR) program and demonstrated proof of principle, but was not rugged enough to deploy to an outside the continental United States (OCONUS) (site for field testing and validation. The initial function of the follow-on effort was to upgrade the existing prototype with better, more advanced equipment that could withstand the stresses of a 3 month OCONUS deployment in an operationally harsh environment (Figure 4).

Figure 3. Original TGER Prototype before Retrofit

Figure 4. TGER after Retrofit

Three of the key improvements identified during testing of the Phase II TGER and applied during the retrofit and fabrication are highlighted below.

1. <u>First Stage Materials Preparation (Industrial Shredder and Separations System)</u>. This component combines several key tasks that are currently done on the original prototype with separately acquired and integrated third-party components. Tasks include shredding, rinsing, auguring, and compacting bioreactor residuals. The Industrial shredder performs these functions as a single component with half of the electrical power required by the original TGER. The new Industrial shredder was retrofitted onto the original prototype and included during fabrication of the second prototype.

2. <u>Second Stage Pelletizer</u>. Testing demonstrated that the size and shape of the pellets were the most critical qualities of gasifier feedstock, followed by pellet density and then proportions of waste content (plastic versus cellulosic, other). Our original view of the feedstock had focused on the latter (i.e., waste content proportions) and had used a less expensive compaction channel for gasifier pellets. Subsequent off-line testing with pellets made with equipment demonstrated a marked improvement in gasifier performance and subsequent engine output. The pelletizer, shown in Figure 5, was included in the second TGER design and was a retrofitted improvement to the original prototype.

3. <u>Stainless Steel Commercial Grade Distilling Column</u>. The stainless steel distilling column was upgraded from standard steel to stainless to prevent the introduction of rust into the distilling apparatus.[9]

Figure 5. Two High Capacity Laboratory Pelletizers Mounted on a Single Table with Casters

3.2 Modifications of Second Prototype.

Fabrication of the second TGER prototype began in early March 2008 and was completed in 3 weeks. During fabrication, additional modifications were applied to the second prototype that could not be applied to the first. These modifications are discussed in more detail below.

3.2.1 Water Circulation System.

The material rinsing water was routed away from the main system through an intermediate sump pump and into a 500 gal tank (see Figure 6), and then routed back into the wash tank on the system using a sump pump. There were several reasons for this modification. First, the intermediate sump pump broke up any large debris (e.g., food slop and paper material) that passed through the sieve. This ensured that the re-circulated liquids would not cause any clogging of the plumbing. Using the large 500 gal tank at ground level also made it easier and more efficient for the operators to monitor the fermentation process and add the necessary biocatalysts.

3.2.2 Rubber/Flexible Plumbing.

The plumbing on the first TGER prototype was fabricated using standard 2 in. PVC pipe. When operating in freezing temperatures, water would collect in the pipes after operation, freeze overnight, and cause the pipes to burst, causing significant delays in operation due to the time required to repair the pipes. Therefore, the second TGER prototype used a flexible rubber hose with quick disconnect fittings instead of pipes, allowing the water to be drained from the hoses after operation to prevent the pipes from freezing. Flexible hosing also eliminated the possibility of pipes breaking due to excessive vibration of the TGER either while in operation or during transport.

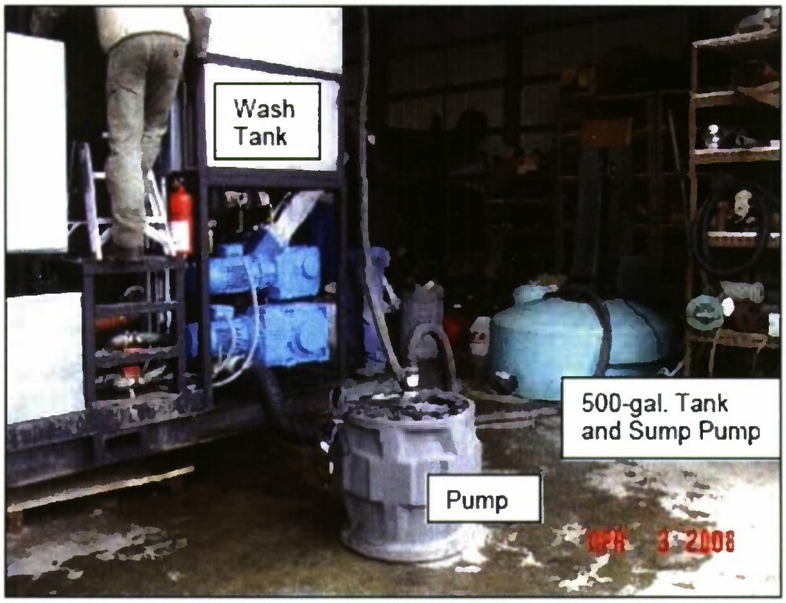

Figure 6. Material Rinsing Water Routed off the Main System through an Intermediate Sump Pump and into a 500 Gal Tank

3.2.3 Chiller.

During testing of the first prototype, a chiller was needed to efficiently and quickly condense the distilled ethanol into a liquid state and collect it in the ethanol fuel tank. Due to design issues, the chiller could not be retrofitted on the first prototype but was included on the second. The chiller cooled a mixture of 50% water and 50% antifreeze and circulated it into a heat exchanger (condenser). In the condenser, the ethanol vapor would condense into liquid ethanol, allowing the TGER to operate efficiently in hotter climates.

3.2.4 Reflux Valve.

The reflux valve is a programmable valve that automatically redirects condensed ethanol from the condenser to either the ethanol storage tank or back to the distillation column at a 5:2 time ratio. By redirecting condensed ethanol back into the distillation column at a 5:2 time ratio, the ethanol purity improved from 80% to 85%.

3.2.5 Pellet Auger/Elevator.

An external pellet elevator was purchased to automate the process of supplying waste derived pellet fuel into the downdraft gasifier (Figure 7). On the original prototype, a technician was required to climb onto the top of the TGER to pour waste pellets from a bucket into the gasifier, a time consuming and unsafe process. The pellet elevator allowed the technician to dump the pellets into a large collection bin at ground level and the pellet elevator

would automatically deliver the correct quantity of pellets into the gasifer based on data received from an infrared sensor suspended over the gasification chamber.

Figure 7. Pellet Auger/Elevator

3.2.6 Centrifuge Pump and Basket Filter Configuration.

On the original prototype, the centrifuge pump and basket filter had to be installed on their side. To achieve optimal performance from the pump and filter, it is necessary to install them upright. The frame on the second prototype was redesigned to accommodate an upright installation of the pump and filter.

4. CURRENT OUTCOME OF TECHNICAL IMPLEMENTATION

Both TGER prototypes underwent a third party assessment conducted by the U.S. Army Aberdeen Test Center (Aberdeen Proving Ground, MD). Three high risk and five medium risk hazards were identified on the TGERs. All risks were mitigated with minor hardware modifications, and sufficient safety devices and equipment were supplied as part of the basic issue items (BII). Given the mission of the Rapid Equipping Force is to quickly respond to field commanders' requests by accelerating new technologies, the two first stage TGER prototypes were deployed by intent at what was considered to be the minimum technical readiness level for field evaluation. TGER assessment during the 90-day deployment to Victory Base Camp, Iraq, met its objectives by identifying the key engineering challenges needed to advance from a first stage scientific prototype to an acquisition candidate system (Figure 8).

Figure 8. Deployed TGER

The Iraq deployment validated the utility of the TGER system as an efficient means to address a complex, mixed, wet, and dry waste stream, while producing power. The science and technology underlying the hybrid design of the TGER is unique and has considerable advantages over other unitary approaches. The engineering of the TGER system and, in particular, the difficulties that arose in having to modify third-party commercial off the shelf equipment to TGER purposes were an expected and commensurate problem.

Overall, the TGER performed well as a system for the first month of deployment. During the second month, unanticipated problems with the downdraft gasifier arose, which required considerable remedial attention by the technicians. With remote coordination with the manufacturer, many of these problems were quickly resolved. However, the overall reliability and performance of the downdraft gasifier was in general decline over the three months, which resulted in considerable down-time during the deployment.

Despite some initial tankage limitations (due to a delay in site prep by the Victory Base Camp DPW) and intermittent performance of the chiller system due to extremely high (120°F) ambient temperatures, the bioreactor performed well during the first month. The chiller was eventually upgraded with one of greater capacity. However, during the final month, the system encountered a compromised heat exchanger, some pumping problems, and apparent loss of biocatalyst efficacy due to heat exposure. The technicians were able to bypass the failed heat exchanger, modify pump elevations, and add fresh biocatalysts to recover system performance.

About half way through deployment, one of the two laboratory pelletizers became inoperative and could not be recovered. This resulted in a shift from a daily to an intermittent duty cycle (every other day) as the operators could not produce sufficient waste fuel pellets to keep the downdraft gasifier running continuously. The downdraft gasifier requires 60 lb/pellets/hr and both pelletizers were needed to meet that throughput.

Alternatively, the biggest issues anticipated prior to deployment (i.e., the viability of the waste processing equipment involving the shredder, material transport/feeding and generator flex-fuel control) performed reliably and were generally trouble free. Our pre-deployment effort on these critical system tasks ensured the system performed reasonably well during the first month, and allowed the other engineering issues to emerge from the background for proper identification and characterization for remedy.

Despite the mechanical issues, when the various elements of the TGER system were pulled together (routinely during the first month, then intermittently during the last 2 months) the system performed remarkably well. Field data demonstrated operations at or near 90% efficiency, with excellent throughput of liquid and dry waste. The system generally conserved water at steady state and no environmental or safety problems emerged.

4.1 General TGER Parameters.

Dimensions (LxWxH).. 200"x88"x99"
Weight... 10,000 lb

Waste Residuals per Day (Ash):
Emissions.. EPA compliant
Consumable Electric Power Produced....................................... max 50 kW
Water Supply .... 600 gal is required to initially charge the system
Manpower to Operate .... 1-2 operators

Consumables:

Biological package, fuel, water, charcoal, and downdraft gasifier filter bags
Lactrol (Antibiotic): 1g/day ($0.26/g)
Glucozyme (Enzyme): 50g/day ($0.89/50g)
Amylase (Enzyme): 50g/day ($2.05/50g)
Yeast: 200g/day ($4.39/200g)
Total cost for biological package: $7.59/day
Downdraft gasifier filter bags need to be replaced every 2 weeks.
50lb of charcoal per month.

Logistical Overhead:

Set-up/breakdown time: three days total to operate the system.

Safety and Health Risk:

Received safety release from ATEC for prototypes, certifying the prototypes safe for human use. TGER will require further safety evaluation to be cleared for soldier operation.

Target MTBEFF:

TGER is composed of several subsystems, each with their own mean time between essential function failures (MTBEFF). The gasifier was the worst performer of the subsystems, with a MTBEFF of about 6 hr. This has caused us to look at other gasification technologies to replace the current gasifier. The pelletizers in the material handling subsystem were the next worst performer. The pelletizers were undersized for the amount of throughput that caused some maintenance problems and breakdowns. The pelletizer MTBEFF was about 48 hr. This problem should be resolved with pelletizers that have the right specifications. Applying the proper upgrades to the gasifier and replacing the pelletizers the target MTBEFF will be 1 month.

4.2 Sub-System Specific Parameters.

Ethanol Production and Consumption
Production .... 12 gal/day
Consumption .... 1 gal/hr

Syngas Production and Consumption
Production .... 65 m^3/hr
Consumption .... 65 m^3/hr

Pellet Production and Consumption
Production .... 60 lb/hr
Consumption .... 60 lb/hr

Power Efficiency
Total Power Generated .... 54 kW
Parasitic Power Demand .... 14 kW

Total Waste Remediated per Day .... 1,752 lb
Solid .... 1,440 lb
Liquid .... 312 lb

Diesel Fuel Consumption per Day .... average 24 gal

Diesel Fuel Saved per Day .... average 86 gal

Although the TGER did not perform to its full potential during the 90 day assessment and validation, it did demonstrate its ability to convert waste to energy and reduce diesel fuel consumption in a harsh operating environment. Below is the system level parameters recorded during live testing in Iraq. Due to equipment problems, the TGER was not able to demonstrate its ethanol production capabilities and provide enough data to statistically evaluate the bioreactor performance. The harsher conditions in Iraq also required more maintenance time for the pelletizer, thus reducing their pellet production capabilities. These issues and others contributed to the reduced fuel efficiency of the TGER while in operation in Iraq.

Ethanol Production and Consumption
Production ....Insufficient Data
Consumption ....Insufficient Data

Syngas Production and Consumption
Production ....65 Nm^3/hr
Consumption ....65 Nm^3/hr

Pellet Production and Consumption
Production 54lb/hr
Consumption ....60 lb/hr

Power Efficiency
Total Power Generated ....54 kW
Parasitic Power Demand ....14 kW

Diesel Fuel Consumption per Day .... average 48 gal

Diesel Fucl Saved per Day .... average 62.4 gal

Below are specific data taken from various days when the TGER was operating at its best in Iraq. Figure 9 illustrates the ability of the TGER to conserve diesel fuel when running at high loads. The specifications for the Kohler 60 kW generator used on the TGER rates the engine's fuel consumption at 4.6 gal gph when < 100% load. One hundred percent (100%) load for the Kohler generator set using a 3-phase, 120/240V 4P8 alternator, at prime rating is 54 kW. The TGER maintained 50 kW of off board power (usable power) for approximately 2 hr. During that same time the engine's diesel fuel consumption was on average 1.5 gph, a diesel fuel savings of 2.76 gph.

Figure 10 illustrates the power efficiency of the TGER. The yellow line represents all the power consumed by the TGER's subsystems and is referred to as parasitic power. All remaining power generated by the TGER (50kW) is available for use by the customer, and is represented by the light blue line. To determine the TGER's power efficiency (pink line), we divided the power available to the customer (light blue line) by the total power generated (dark blue line). The TGER's average power efficiency was approximately 77.37% during the recorded timeframe.

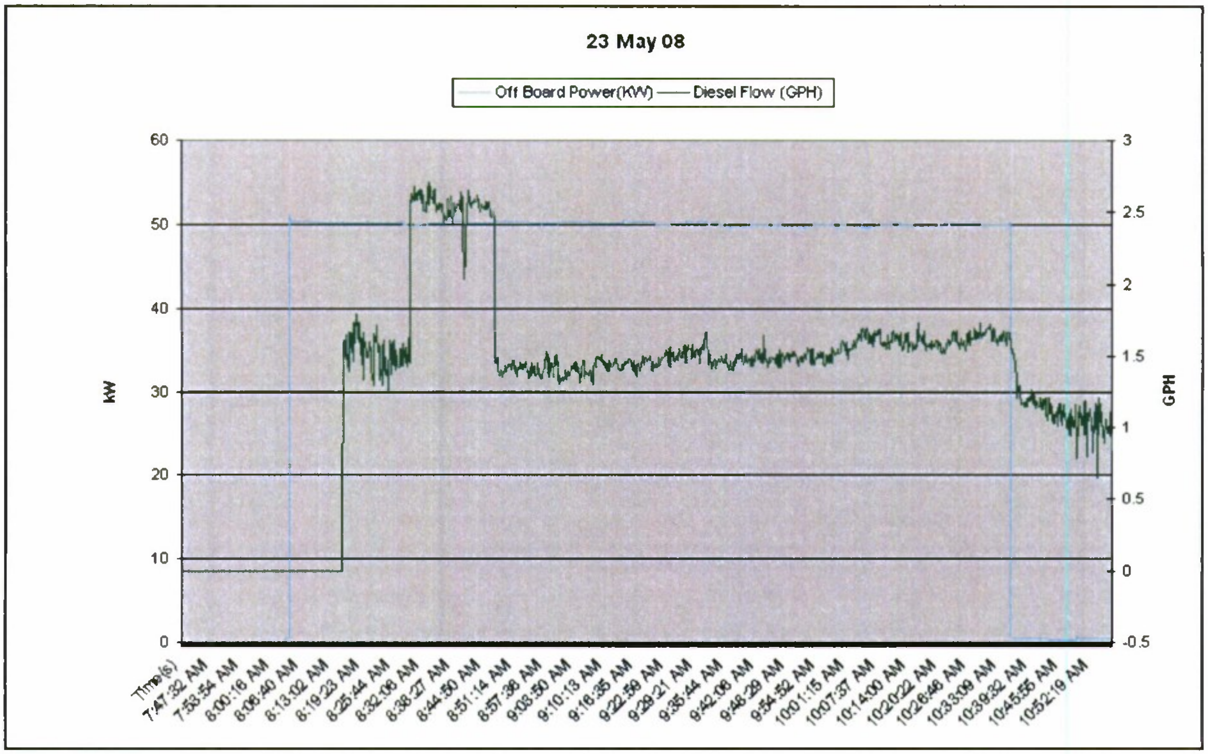

Figure 9. Example Test Data (Fuel/Power over Time)

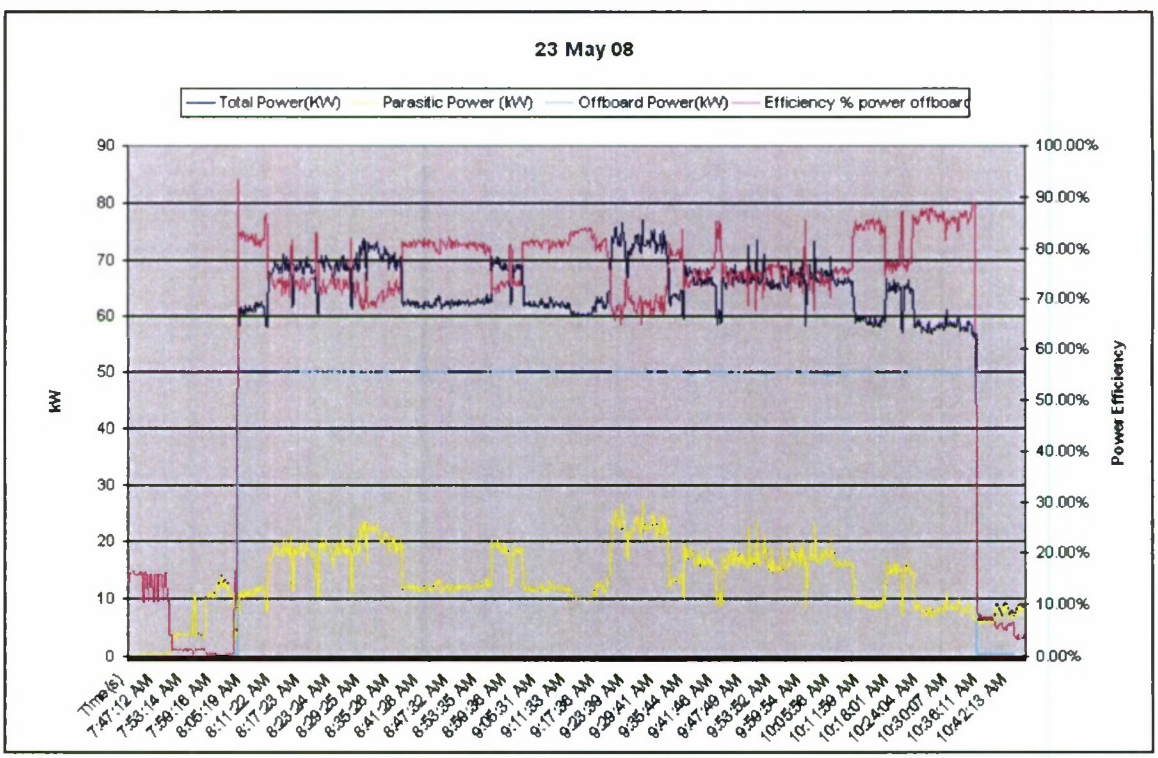

Figure 10. Example Test Data (Power Components over Time)

Figure 11 illustrates the TGER's ability to continue to conserve diesel fuel in adverse environmental conditions. The generator exceeded the recommended load of 54kW and generated 55.5kW of off board power while consuming only 2.5 gph of diesel fuel. The most likely cause of the increase in fuel consumption from 1.5 to 2.5 gph was due to foreign debris (i.e., sand and dust) entering the system and causing the gasifier filters to clog, thereby reducing the amount of syngas supplied to the engine. This forced the engine to compensate by supplying more diesel fuel into the engine to maintain 55.5kW of off board power. Even under these suboptimal conditions, the TGER was able to conserve 2.23 gph of diesel fuel.

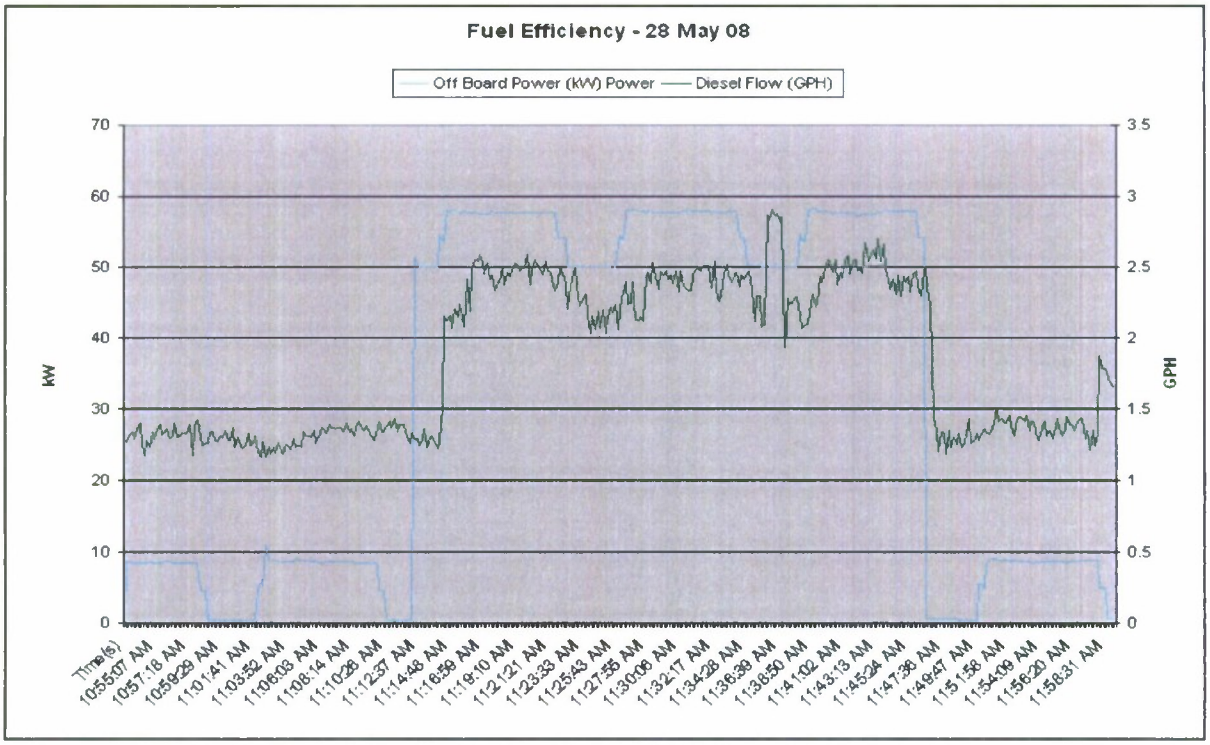

Figure 11. Fuel Efficiency and Power (28 May 08).

Table 3 shows data taken during field testing on 30 May 08 that was input into the TGER Energy Conversion Model. The model calculates the percent contribution that diesel fuel versus biofuels has to generating electrical energy. The model calculated that, of the total energy produced, the biofuels contributed 77.26% of the required energy and diesel fuel contributed 22.74%.

Table 3. Data from TGER Energy Conversion Model

Feed Materials (daily) - 30 MAY 08

Garbage (gallons)	70	20% paper, 50% cardboard, 30% plastic
Garbage (lbs)	399	
Food (gallons)	40	
Diesel (galllons)	9	

Energy Content of Feed

Total (lb)	Component	Heats of Comustion (btu/lb) LHV	Total Energy (BTU)	Total Energy (kWhr)
2.0	Carbohydrates	7200	14394.24	4.21871
279.3	Paper/Cardboard	8000	2234400	654.8652
59.9	Plastic-Polyethylene Terephthalate	10250	613462.5	179.7956
59.9	Plastic-Polystyrene	17800	1065330	312.2304
62.8	Diesel (DF2)	18397	1155700	338.7162
		Total	5083286	1489.826

Electrical Energy Production

Total (kWhr)	343
Offboard (kWhr)	230

Total Thermal-to-Electrical Energy Conversion Efficiency (% of energy content of feed)
23.0%

Offboard Energy Conversion Efficiency (% of thermal energy content of feed)
15.4%

Diesel Fuel Savings (gallons)
33

Energy Delivery Efficiency (% of electrical energy for offboard use)
67.1%

	% Contribution to Feed Energy
Diesel	22.74%
Biofuels	77.26%

Figure 12 illustrates the effect of the introduction of ethanol on fuel consumption of the generator. Fuel consumption matches closely with the increase in power output until 1:30 pm, after which the fuel consumption drops off abruptly, while the power output remains relatively steady. At 1:30 pm, ethanol was introduced into the engine at rate of 0.5 gph causing the diesel fuel consumption rate to drop by more than 0.25 gph. Ethanol was supplied to the engine for approximately 30 min until mechanical difficulties with the ethanol pump began to

occur and forced the operators to turn the pump off. When the ethanol pump is turned off the diesel fuel consumption gradually goes up while the power output remains relatively steady.

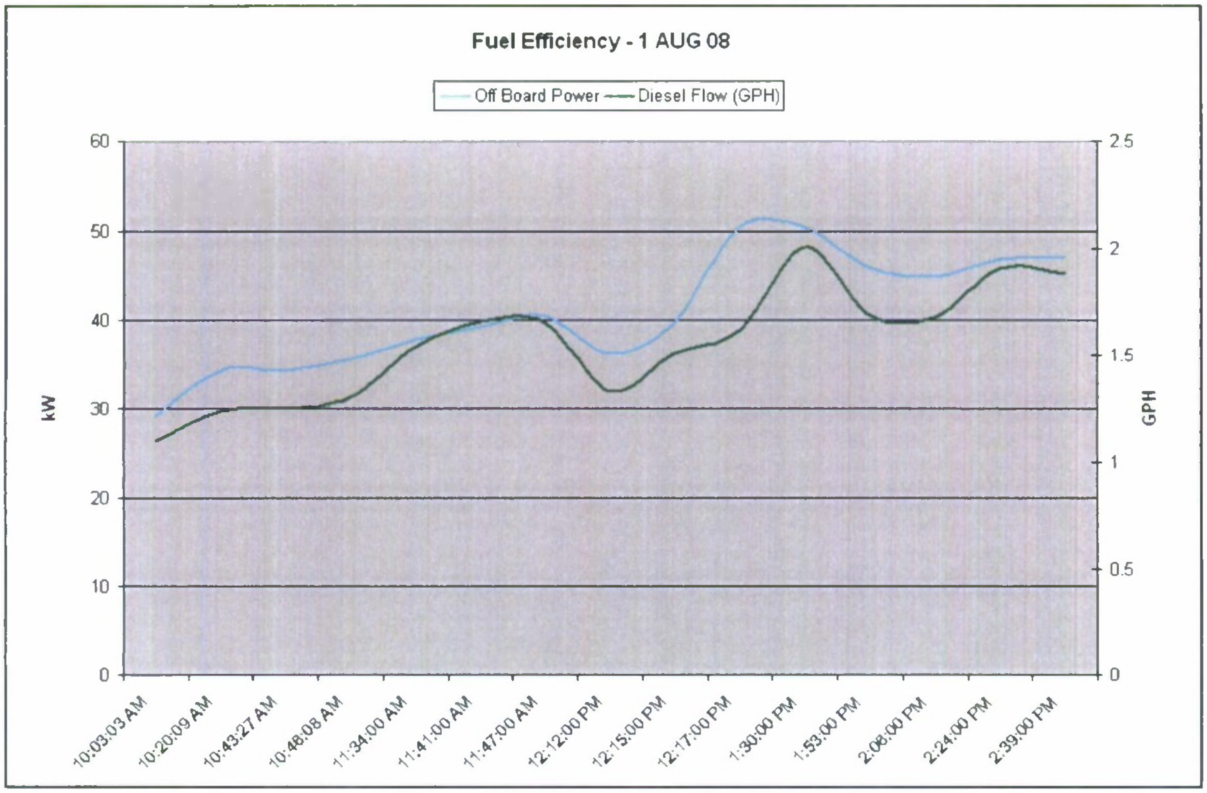

Figure 12. Fuel Efficiency and Power (1 August 08).

Table 4 shows the use of the TGER Energy Conversion Model to analyze the performance of the TGER on 1 August 08. Biofuels contributed 92.92% of the required energy to generate electricity and diesel fuel contributed 7.08%. This shows that the TGER can run almost entirely on biofuels, although the increase in biofuel contribution did have a negative affect on the thermal to electrical conversion efficiency. The increase in the contribution of energy from biofuels lowered the thermal to electrical conversion efficiency from 23% on 30 May 08 to 16.8% on 1 August 08, which is attributable to the fact that the Kohler generator was specifically designed to run on diesel, rather than biofuels.

Table 4. Additional Data from the TGER Energy Conversion Model

Feed Materials (daily) -01 AUG 08		
Garbage (gallons)	90	20% paper, 50% cardboard, 30% plastic
Garbage (lbs)	513	
Food (gallons)	58	
Diesel (galllons)	3	

Energy Content of Feed

Total (lb)	Component	Heats of Comustion (btu/lb) LHV	Total Energy (BTU)	Total Energy (kWhr)
2.9	Carbohydrates	7200	20871.65	6.11713
359.1	Paper/Cardboard	8000	2872800	841.9695
77.0	Plastic-Polyethylene Terephthalate	10250	788737.5	231.1657
77.0	Plastic-Polystyrene	17800	1369710	401.439
20.9	Diesel (DF2)	1B397	385233.2	112.9054
		Total	5437352	1593.597

Electrical Energy Production	
Total (kWhr)	267.5
Offboard (kWhr)	221.2

Total Thermal-to-Electrical Energy Conversion Efficiency (% of energy content of feed)
16.8%

Offboard Energy Conversion Efficiency (% of thermal energy content of feed)
13.9%

Diesel Fuel Savings (gallons)
27

Energy Delivery Efficiency (% of electrical energy for offboard use)
82.7%

	% Contribution to Feed Energy
Diesel	7.08%
Biofuels	92.92%

5. EXPERT COMMENTARY AND FIVE YEAR VIEW

The TGER is a transportable, skid-mounted device capable of converting waste products (paper, plastic, packaging, and food waste) into electricity via a standard 60kW diesel generator. Additionally, the system can use available local biomass as a feedstock. Waste materials are converted into bio-energetics that displace the diesel fuel used to power the

generator set. The system also co-produces excess thermal energy, which can be used via a "plug and play" heat exchanger to drive field sanitation, shower, laundry, and/or cooling devices. With additional engineering, the TGER could include a small subsystem to recover water introduced with the wet waste and produce potable water to further reduce logistics overhead. The system requires a small "laundry packet" of enzymes, yeasts and industrial antibiotics to support the biocatalytic subsystem. The residuals from waste conversion are environmentally benign including simple ash, which can be added to improve soil for agriculture and carbon dioxide.

The TGER will deploy on a XM 1048 5-ton trailer and is designed to support a 550 man Force Provider Unit (FPU), which produces approximately 2,200 lb of waste daily. On a daily operational basis, this would conserve approximately 100 gal of diesel. The capability for such conversion would provide immediate and responsive energy requirements for expeditionary operations, as well as yielding estimated cost savings of $2,905/day.[10] A projected fielding plan for the TGER involves identification of current Modified Table of Organization and Equipment (MTO&E) trailers associated with FPU kitchen support, which would then be modified to include the waste conversion technology. This would avoid any changes to the MTO&E or prime mover designation. Estimations indicate that the additional tasks associated with maintenance support for the operator and mechanic would not exceed those standards for the assigned Military Occupational Specialty and Generator Mechanic. Higher order support may follow a Contractor Logistics Support or low density support plan similar to that for the reverse osmosis purification unit equipment.

Anticipated field employment of the system is such that the TGER would be pulled by the assigned 5-ton family of medium tactical vehicles assigned to accompany the FPU Containerized Kitchen. Upon occupation of the FPU site, the TGER would start up initially on diesel fuel alone. This would provide immediate power to the kitchen and begin to heat up/power the system components. As waste is developed from the kitchen, it will be introduced to the TGER, and the two energetic materials (synthetic gas and ethanol) will begin to displace the diesel fuel. By 6 to 12 hr (depending on the waste stream), the TGER will run on 98% waste energetics and is capable of running for 12 hr with a 1 hr maintenance shut-down intervening.

Improvements for future models revolve around three subsystems: the gasifier, bioreactor, and materials handling. The current downdraft gasifier equipment is too complicated and unreliable under desert conditions. However, modifications to the current design could reduce the complexity of the system and, with a thorough inspection, repair, and evaluation by the manufacturer. We believe a number of alterations to the downdraft gasifier would mitigate its reliability problems. Ultimately, it would be advantageous to consider alternative thermo-chemical approaches.

The issues with the bioreactor are much less complex and more easily addressed, as the system was custom built by Purdue University and several supporting subcontractors. Repairing and upgrading this system will primarily involve replacing and upgrading the two heat

exchangers, modifying the system software to accommodate the changed thermo-dynamics and thermal management, and adjusting the "plumbing" of the ethanol collection and delivery system.

During the intervening 18 months since the TGER fabrication, the commercial field of biomass fuel processing has greatly expanded. There are a number of new options for third party equipment such as improved shredders, pelletizers, and pellet drying systems that did not exist previously.

6. CONCLUSIONS

Throughout the course of the 15 month program the Tactical Garbage to Energy Refinery (TGER) underwent testing in a variety of conditions and environments. Performance characteristics of the TGER varied in each environment and provided valuable information as to how to improve the overall design of the TGER to achieve what we believe to be the optimal theoretical performance characteristics shown in Table 5.

Table 5. Theoretical/Optimal TGER Performance Data

Power Output	Power Efficiency	Diesel Consumption Rate	Ethanol Consumption Rate	Ethanol Production Rate	Solid Waste Processing Rate (Pellet Production)	Liquid Waste Processing Rate	Total Waste Processing Rate	Diesel Savings
54 kW	90%	1 gph	1 gph	1 gph	60 lbs/hr	13 lbs/hr	1,752 lbs/day	3.6 gph

Prior to the deployment to Victory Base Camp, the TGER underwent testing in a controlled environment at Purdue University (West Lafayette, IN). The fuel consumption of all three fuels (syngas, ethanol, and diesel) was measured at varying loads using digital flow rate sensors as seen in Table 6.

Table 6. Power vs. Fuel Consumption Table Recorded at Purdue University

	POWER	Idle	25kW	35kW	45kW	55kW
FUEL						
Diesel		100%	1.3 gph	1.0 gph	1.2 gph	1.0 gph
Fuel Gas		0 scmh	57 scmh	65 scmh	60 scmh	65 scmh
Ethanol		0 gph	0 gph	0 gph	.5 gph	1 gph

Although the TGER did not perform as well in Iraq as it had when in a controlled environment at Purdue University, it did demonstrate the ability to conserve fuel and remediate waste in a forward deployed operational environment. Table 7 shows the TGER's performance characteristics when it was running under optimal conditions at Victory Base Camp. With improved engineering and further development, all of these performance characteristics can be improved, maximizing the TGER's potential as a viable portable power generation system.

Table 7. TGER Performance Data Set Recorded at VBC

Average TGER Performance Data at Victory Base Camp						
Power Efficiency	**Diesel Consumption**	**Pellet Consumption**	**Solid Waste Processing** (Pellet Production)	**Liquid Waste Processing**	**Total Waste Processing**	**Diesel Saved**
~80%	2 gal/hr**	60 lb/hr	54 lb/hr	13 lb/hr	1,752 lb/day	2.6 gal/hr

Blank

LITERATURE CITED

1. Grover, V.I; Grover, V.K.; Hogland, W. 2002 *Recovering Energy from Waste: Various Aspects*. Plymouth, UK. (ISBN 978-1-57808-200-1).

2. Fellner, J.; Cencic, O.; Rechberger, H. A New Method to Determine the Ratio of Electricity Production from Fossil and Biogenic Sources in Waste-to-Energy Plants. *Environ. Sci. & Technol.* **2007**, *41, 7*, 2579-2586.

3. Nektalova, T. (2008) "Energy Density of Diesel Fuel." The Physics Factbook. 2006 Hypertextbook. http://hypertextbook.com/facts/2006/TatyanaNektalova.shmtl. (Accessed June 2009).

4. Stoft, S. (2008) "With Only 2/3 the Energy of Gasoline, Ethanol Costs More per Mile." Exact Low Energy Content of Ethanol. *zFacts.*; http://zfacts.com/p/436.html. (Accessed June 2009).

5. Davis, R.A. MS Thesis, Purdue University, West Lafayette, IN, 2006.

6. Gray, K.A.; Zhao, L.; Emptage, M. Bioethanol. *Curr. Opinion Chem. Biol.* **2006**, *10, 2*, 141-146.

7. Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. Environmental, Economic and Entergetic Costs and Benefits of Biodiesel and Ethanol Biofuels. *Proc. Natl. Acad. Sci.* **2006**, *103*, 11206-11210.

8. Chandra, R.P.; Bura, R.; Mabee, W.E.; Berlin, A.; Pan, X.; Saddler, J.N. Substrate pre-treatment: the Key to Effective Enzymatic Hydrolysis of Lignocellulosics? *Adv. Biochem. Eng./Biotechnol.* **2007**, *108*, 67-93.

9. Patzek, T.W. Thermodynamics of the Corn-Ethanol Biofuel Cycle. *Curr. Rev. Plant Sci.* **2004**, *23*, 519-567

10. Canes, M.E.; Werle, C.P.; Philipp, M.W.; Mosko, S.A. An Analysis of the Energy Potential for Field Waste in the Field; Logistics Management Institute: McLean, VA, **2004**; UNCLASSIFIED Report (AD-B296 097).